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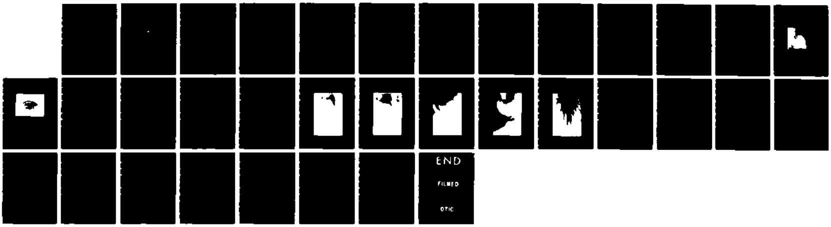

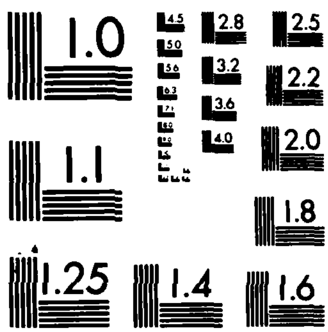

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CONTRACTOR REPORT

BURNING TIME AND SIZE OF ALUMINUM, MAGNESIUM,

ZIRCONIUM, TANTALUM, AND PYROFUZE PARTICLES

BURNING IN STEAM

Yair Chozev and Jacob Kol

July 1985

Approved for public release; distribution unlimited.

Prepared for: Naval Surface Weapons Center
White Oak Laboratories
Silver Springs, MD 20910

NAVAL POSTGRADUATE SCHOOL
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The work reported herein was carried out for the Naval Postgraduate School by Mr. Jacob Kol under Contract N62271-84-M-3357 and Mr. Yair Chozev under Contract N62271-84-M-3055. The work presented in this report is in support of "Underwater Shaped Charges" sponsored by the Naval Surface Weapons Center. The work provides experimental results for burning time and size of aluminum, magnesium, zirconium, tantalum and pyrofuze particles in steam. The project at the Naval Postgraduate School is under the cognizance of Distinguished Professor A. E. Fuhs who is principal investigator.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wires of various metals were exploded in a steam atmosphere. The metals investigated were aluminum, magnesium, tantalum, zirconium, and pyrofuze. Exploding wires generated numerous hot, small particles. Using photography, the burning time and particle sizes were measured. Typical results are as follows: 125 ± 25 micron diameter aluminum burns in 3.8 ± .75 ms; 175 ± 35 micron diameter magnesium burns in 3.8 ± .75 ms; 125 ± 25 micron diameter zirconium in 25 to 31 ms; 125 ± 25 micron diameter tantalum in 24 to 50 ms;

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and 125 ± 25 micron pyrofuze in 30 to 50 ms. The atmosphere was pure saturated steam at approximately 20 psig.

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ABSTRACT

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Wires of various metals were exploded in a steam atmosphere. The metals investigated were aluminum, magnesium, tantalum, zirconium, and pyrofuze. Exploding wires generated numerous hot, small particles. Using photography, the burning time and particle sizes were measured. Typical results are as follows: 125 ± 25 micron diameter aluminum burns in 3.8 ± .75 ms; 175 ± 35 micron diameter magnesium burns in 3.8 ± .75 ms; 125 ± 25 micron diameter zirconium in 25 to 31 ms; 125 ± 25 micron diameter tantalum in 24 to 50 ms; and 125 ± 25 micron pyrofuze in 30 to 50 ms. The atmosphere was pure saturated steam at approximately 20 psig.

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I. INTRODUCTION

The energy released by metals burning in steam has several important applications including torpedo propulsion, nuclear reactor safety, underwater vehicles, underwater ordnance, etc.

This report continues the studies that were performed by Hallenbeck [1] and Kol, Fuhs and Berger [2] which are related to underwater shaped charge investigations.

Investigation of burning time of aluminum, magnesium, tantalum, zirconium and pyrofuze particles in steam were rarely found in the literature.

Leibowitz et. al., [3] ignited aluminum particles of diameter of 360 μm in water and steam by laser beam and measured the burning-time of the reacting particles. In the cases of low amount of reaction (T=25°C, P=0.03 ATM where T and P are the water temperature and pressure, respectively) the burning-time was 5 to 10 ms. In the cases of complete reaction (T=100°C, 181°C and P=1, 10 ATM respectively) long burning times of 213 ms were measured. The amount of reaction is according to amount of alumina formation.

Cassel et. al., [4] measured the burning time of magnesium particles at atmospheric pressure with O_2, air, premixed $2O_2$ + 8 Ar and $2O_2$ + 8He at 1200K ambient temperature and found that 120 μm particles burned 16.8 ms in air, 15.75 ms in $2O_2$ + 8 Ar and 11.5 m in $2O_2$ + 8He . The burning-time in O_2 was one tenth that in air.

Pruchukho et. al., [5] measured the burning time of magnesium particles in diameter from 34 to 184 μm and in ambient temperature of 1800°C. For the particles of 90 μm at 1 ATM in water vapor, the burning time of 1 ms was obtained while in mixture of 35%H_2O and 65%N_2 at 1 ATM and ambient temperature from 1050°C to 1150°C, the burning time was 2 ms. For particles of 180 μm the burning time was 16 ms in the same mixture.

Ozerov et. al., [6] measured the burning time for aluminum and magnesium in 1800°C water vapor. The burning time in 1 ATM for 120 μm aluminum particles was 18 ms and for 165 μm magnesium particles was 12 ms. The burning time of 148 μm aluminum particles in 3 ATM was 30.5 ms.

Nelson et. al., [7] measured the burning time of 525 μm zirconium particles in mixtures of O_2, He/O_2 and Ar/O_2 at 0.82 ATM and found 200 ms for 65%He + 35%O_2 and even longer burning time for 65% Ar + 35%O_2.

Harrison [8] measured burning velocities of zirconium wires of 1 and 0.5 mm diameter in atmospheric pressure and mixtures of air and oxygen and found burning time longer than magnesium.

Data for burning time was not found for tantalum and pyrofuze particles. This report summarizes the burning time measurements and particle size measurements for aluminum, magnesium, zirconium, tantalum and pyrofuze burning in steam.

II. EXPERIMENTAL

A. Experimental Procedure

The experiments were conducted in pressure vessel which consisted of a twelve inch high stainless steel cylinder, 10.75 inches diameter with four evenly spaced, 5 inch diameter observation ports welded into its circumference. One inch thick. Schlieren quality, borosicalate crown glass (BK-7) was installed in each port. Two Watlow Band Heaters were used to heat the apparatus to operating temperature and four additional Watlow Heaters were mounted on observation ports in order to prevent steam condensation during experiments. An Omega model 157 Digital Controller was used for temperature stabilization. The experiments were conducted in pressure range of 20 to 35 psi and steam temperature of 180°C. Thermocouples were mounted in different locations inside the chamber to measure the internal temperature.

The aluminum, magnesium, tantalum, zirconium and pyrofuze particles were generated by the exploding wire technique. The 5 cm length wire was mounted between two holders and the ignition energy transferred to the wire.

Particle burning time was measured using Pentax 35 mm still camera equipped with high speed light chopper (see Figure 1). Kodak ektachrome 200 ASA film, 400 ASA TRI-X PAN film and Polaroid 40 ASA film were used for photography of the time events along particle tracks.

B. High Speed Light Chopper

The light chopper was assembled from an Universal Electric Company motor and a 8 inch diameter balanced disc. The motor speed after loading was 6500 RPM, and the chopping frequency was increased by using fifteen 1 inch diameter holes around the circumference of the disc. The on-off ratio of the chopping was designed to be 67 percent on time and 33 percent off-time. The chopping time is calculated as follows:

$$T_1 \text{ chopping} = \frac{60}{6500 \times 15} = 0.62 \text{ [ms] (for 15 holes)}$$

$$T_2 \text{ chopping} = \frac{60}{6500 \times 12} = 0.77 \text{ [ms] (for 12 holes)}$$

where T_1 and T_2 are the chopper periods for 15 and 12 holes respectively.

Figure 1. Photography with High Speed Chopper

a. High Speed Light Chopper

b. 35 mm Pentax Camera

C. The Quenching Technique for Particle Size Measurement

The diameter of the particles was measured by comparing the quenched particles to standard wires. The quenching technique for the burning particles is shown in Figure 2.

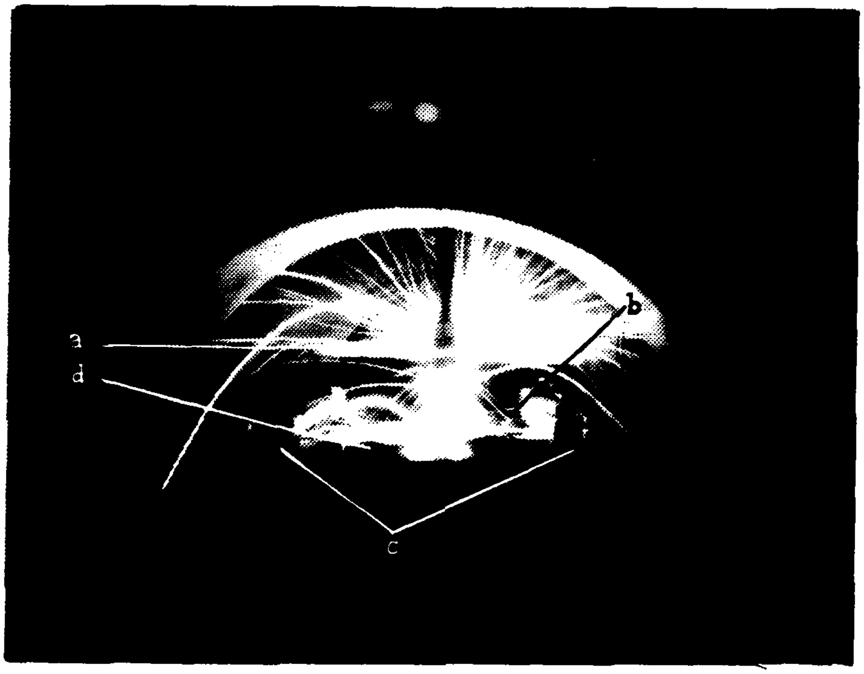

Figure 2. The Quenching Technique Configuration for Particle Quenching

a. Particle angular filter made of teflon plate

b. An aluminum foil impact suppressor

c. The aluminum foil holders

d. Stainless steel collector plate (smeared with silicon grease).

The aluminum foil was assembled at a distance 29 ± 0.5 mm below the wire while the plate was assembled 35 ± 0.5 mm below the wire.

III. RESULTS

A. Burning Time Measurement

The experimental conditions of burning time measurements are summarized in Table 1. In the following tests, the 55 mm focal length lens was used. Representative photographs of burning time experiments are shown in Figure 3 through Figure 7.

B. Distribution Functions of Burning Time

The distribution functions of burning time results of aluminum, zirconium, magnesium, tantalum and pyrofuze particles are shown in Figure 8. The burning time of aluminum particles is less than 27 ms where the maximum of the distribution function is for 3.75 ms. The burning time of magnesium particles is less than 14 ms, and the maximum of the distribution function is 3.75 ms.

The burning time of zirconium particles is from 6.5 to 39.5 ms and the maximum of the distribution function is from 25 to 30 ms. The burning time for tantalum particles is longer than that of zirconium particles and is from 9.5 to 91 ms. The distribution function is quite uniform where the maximum is from 24 to 28 ms. The burning time of pyrofuze particles is from 12 to 97 ms and the maximum of an almost uniform distribution function is from 30 to 50 ms. The total number of the particles tracks that were analyzed for different metals were as follows: 40 tracks of aluminum, 22 tracks of pyrofuze, 21 tracks of magnesium and zirconium and 18 tracks of tantalum.

TABLE 1 Burning Time Measurement

TEST NUMBER	METAL	FILM [ASA]	f NUMBER	PRES. [PSI]	TEMP. [F]	*BURNING TIME [ms]	*FLAME ZONE WIDTH [mm]
1	Aluminum	40	2.4	25	380	N/A	N/A
2	Aluminum	40	2.8	27.5	365	6.1,3.1	2.15,1.3
3	Aluminum	40	2.8	22.5	360	8.5	2.8
16	Aluminum	200	5.6	22	370	N/A	N/A
17	Aluminum	200	5.6	27	390	N/A	N/A
18	Aluminum	200	5.6	39	380	N/A	N/A
19	Aluminum	200	5.6	20	390	3.6,3.6,3.05,4.3, 4.9,13.4,15.9,4.3	.78,.78,.61,.26,.78,1.04 1.04,.78
36	Aluminum	200	5.6	34	380	6.7,10.4,6.7,>15	0.95,0.95,.78,1.56
37	Aluminum	400	8	21	360	7.7,6.2,5.4,3.9,6.9	.73,.66,.66,.55,.66
38	Aluminum	400	8	20	360	14.6,2.7,27,10.8, 3.9	.6,1.11,1.02,0.6,.37
39	Aluminum	400	8	22	390	3.9,15.4,7.7,3.9,5.4,7.7 10.8,5.4,4.6,3.9,4.6	0.56,1.02,.74,.28,.28, .65,.83,.47,.37,.55,.46
40	Aluminum	400	8	20	380	N/A	N/A
54	Aluminum	400	8	22	340	4.6,2.3,3.1,3.5	.49,.39,.29,.29
4	Magnesium	40	2.4	21	400	7.9,3.7,3.7,2.4	3,2,1.5,2.6,1.7
5	Magnesium	40	2.4	27.5	370	7.3,2.4	3,4.5,2.6
6	Magnesium	40	2.8	25	400	7.3,3.1	3,1.7
7	Magnesium	40	2.8	23	400	N/A	N/A
20	Magnesium	200	5.6	20	390	N/A	N/A
21	Magnesium	200	5.6	17	380	4.3,3.7,3.1	.78,.69,.69
22	Magnesium	200	5.6	20	370	7.3,6.1,9.8	.78,1.04,1.12
23	Magnesium	200	5.6	27	380	6.1,2.4	0.86,0.78
41	Magnesium	400	8	22	370	N/A	N/A
42	Magnesium	400	8	20	400	N/A	N/A
43	Magnesium	400	8	24	390	4.6	.7
55	Magnesium	400	8	20	380	N/A	N/A
56	Magnesium	400	8	22	350	3.1,2.3,3.9,13.9,6.93, 3.1	.53,.65,.75,0.74,0.68, 0.41

TABLE 1 (CONTINUED)

TEST NUMBER	METAL	FILM [ASA]	f NUMBER	PRES. [PSI]	TEMP. [F]	*BURNING TIME [ms]	*FLAME ZONE WIDTH [mm]
8	Zirconium	40	9.5	27	400	23.8	0.43
9	Zirconium	40	8	35	400	N/A	N/A
24	Zirconium	200	16	33	400	33.6,27.5,31.7,31.7,20.1 20.7,24.4	.6,.43,.51,0.6,.48,.34, .43
25	Zirconium	200	16 + ND 0.3	28	400	9.2,17.1,34.2	.34,.25,.6
26	Zirconium	200	16 + ND 0.3	22	400	N/A	N/A
27	Zirconium	200	16 + ND 0.3	21	390	N/A	N/A
44	Zirconium	400	16 + ND 0.3	36	380	N/A	N/A
45	Zirconium	400	16 + ND 0.3	21	390	23.9,6.2	.18,.18
46	Zirconium	400	16 + ND 0.3	34	400	40,31.5,15.4	.26,.26,.18
47	Zirconium	400	16 + ND 0.3	20	390	N/A	N/A
48	Zirconium	400	16 + ND 0.3	30	380	12.3	.18
57	Zirconium	400	16 + ND 0.3	24	370	21.6,10.8,8.5,12.3	0.22,.18,.13,.18
58	Zirconium	400	16 + ND 0.3	27	390	N/A	N/A
10	Tantalum	40	8	27.5	400	>55	0.66
11	Tantalum	40	8	26	400	N/A	N/A
12	Tantalum	40	9.5	22	400	43,24	0.66,0.5
13	Tantalum	40	9.5	32	360	N/A	N/A
28	Tantalumm	200	16 + 0.3 ND	28	400	26.2,33.6,26.8,55,91.5	.3,.39,.35,.69,.47
29	Tantalum	200	16 + 0.3 ND	27	390	42.7,30.5,85.4,11.6,9.2, 22.6,36.6	.26,.3,0.5,.17,1.3,.37, .26
30	Tantalum	200	16 + 0.3 ND	50	350	26.8,13.4	.43,.26
31	Tantalum	200	16 + 0.3 ND	34	370	18.3	.17
32	Tantalum	200	16 + 0.3 ND	29	360	N/A	N/A
33	Tantalum	200	16 + 0.3 ND	33	390	N/A	N/A
49	Tantalum	400	16 + 0.3 ND	32	400	N/A	N/A
50	Tantalum	400	16 + 0.3 ND	21	360	N/A	N/A
59	Tantalum	400	16 + 0.3 ND	24	390	N/A	N/A

TABLE I (CONTINUED)

TEST NUMBER	METAL	FILM [ASA]	f NUMBER	PRES. [PSI]	TEMP. [F]	*BURNING TIME [ms]	*FLAME ZONE WIDTH [mm]
14	Pyrofuze	40	9.5	21	350	18.3,12.4,19.2	.33,0.17,0.39
15	Pyrofuze	40	8	33	400	93,49,30,56,49	0.82,0.63,.66,.4,0.66
34	Pyrofuze	200	16 + 0.3 ND	22	390	24.4,42.7,53.1,48.8,79.3 42.7	.86,.78,.78,.44,.78,.6
35	Pyrofuze	200	10	40	370	30.5,45.8,15.9,97.6,67, 70.2,51.9,67	.43,.78,.43,.78,.52,.43, .52,.69
51	Pyrofuze	400	16 + 0.3 ND	46	350	N/A	N/A
52	Pyrofuze	400	16 + 0.3 ND	22	390	N/A	N/A
53	Pyrofuze	400	16 + 0.3 ND	21	390	N/A	N/A

* Each burning time was measured until onset of the supercooling event.

Figure 3. Burning Time Measurement of Aluminum Particles

Figure 4. Burning Time Measurement of Magnesium Particles

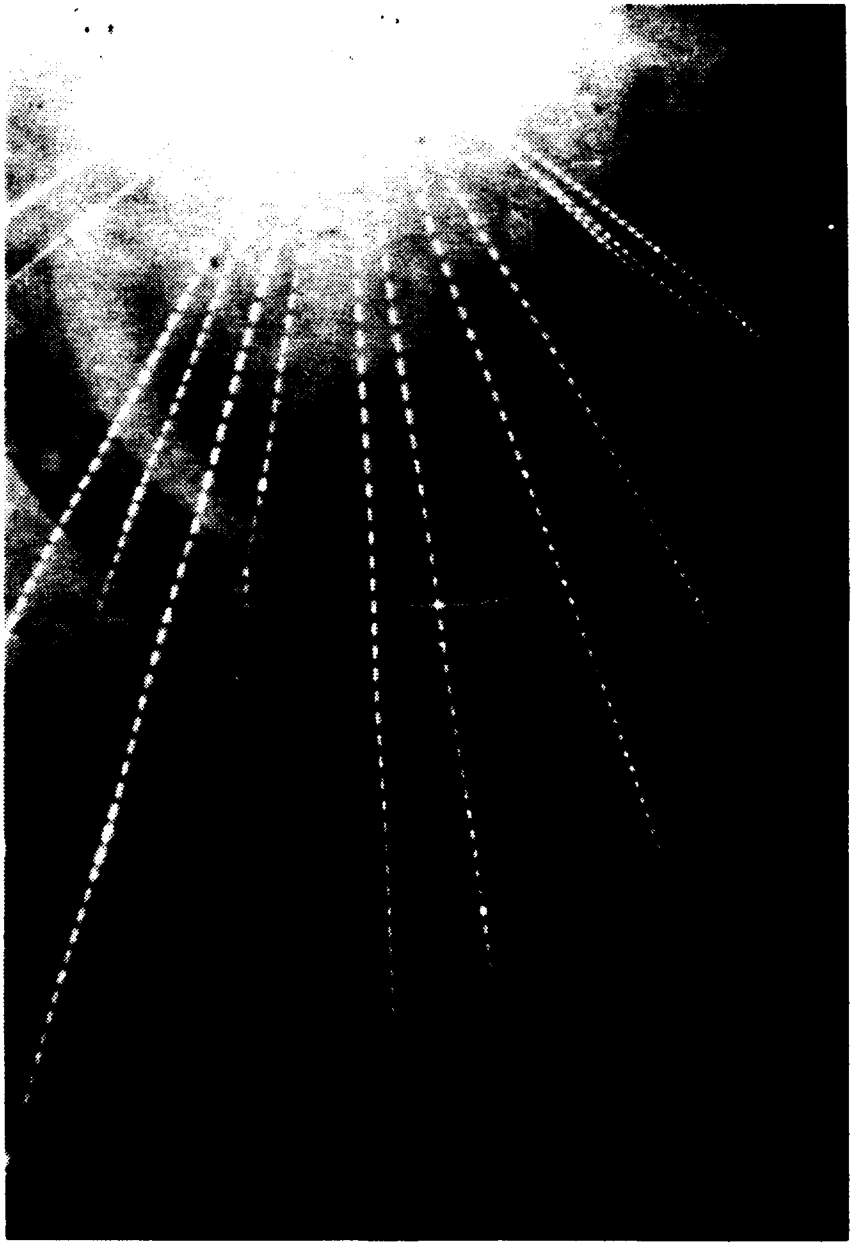

Figure 5. Burning Time Measurement of Zirconium Particles

Figure 6. Burning Time Measurement of Tantalum Particles

Figure 7. Burning Time Measurement of Pyrofuze Particles

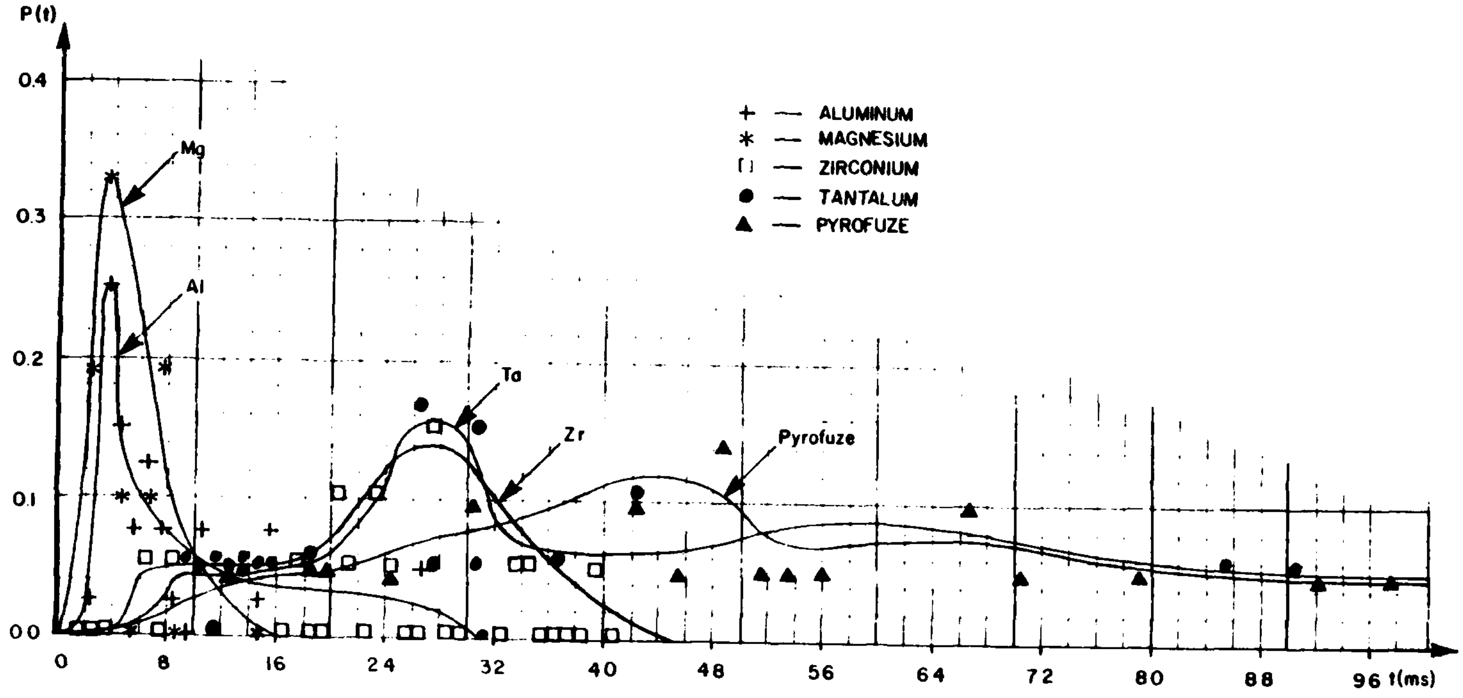

Figure 8. Distribution Functions of Burning Time for $A\ell$, Mg, Zr, Ta and Pyrofuze (see Table 1).

C. Distribution Functions of Particle Size

The distribution functions of particle sizes of aluminum, magnesium, zirconium, tantalum and pyrofuze as were measured by the quenching technique are shown in Figure 9. The locations of the maxima of the various distribution functions is similar, from 0.125 to 0.175 mm, but the tails are different. For aluminum and magnesium the distribution functions have distinct maxima and the greatest particles are about 0.55 mm. The distribution functions of tantalum and pyrofuze have a long tails extending to a size of 1.85 mm. The distribution function of zirconium is about the same as for aluminum and magnesium.

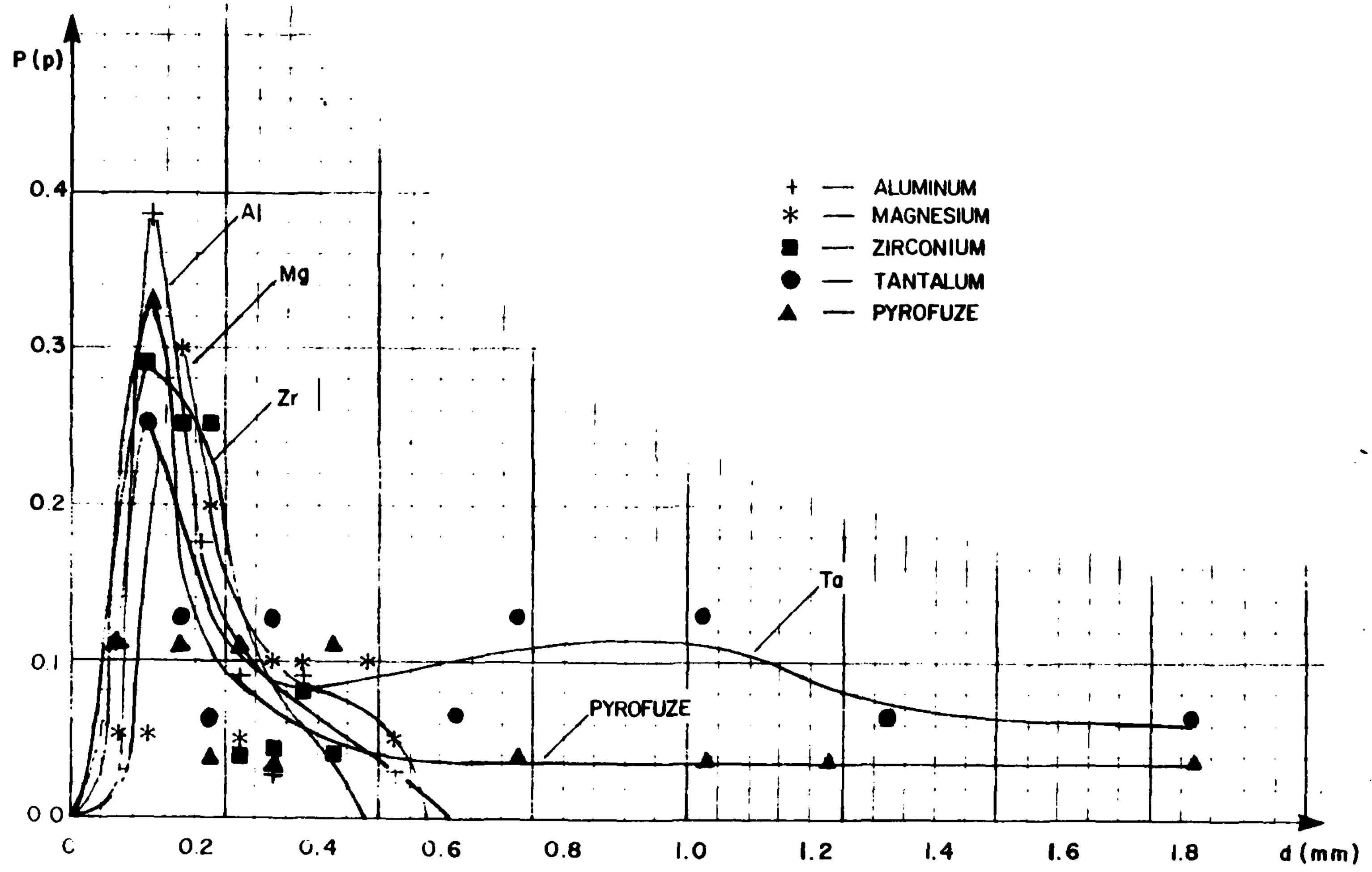

Figure 9. Distribution Functions of Particle Diameter for Aℓ, Mg, Zr, Ta and Pyrofuze (The same conditions as in Table 1).

D. Summary of Results of Burning Time and Particle Size

The summary of results of burning time and particle size measurements is shown in Table 2.

METAL	BURNING TIME LIMITS [ms]	*t_{MPV} [ms]	PARTICLE SIZE LIMITS [μm]	*D_{MPV} [μm]
Aluminum	2-28	3.75 ± .75	75 - 550	125 ± 25
Magnesium	2-14	3.75 ± .75	75 - 550	175 ± 35
Zirconium	6.5-39.5	25 - 31 ± 1.5	75 - 450	125 ± 25
Tantalum	9.5-91	24 - 50 ± 1.5	75 - 1850	125 ± 25
Pyrofuze	12-97	30 - 50 ± 1.5	75 - 1850	125 ± 25

Table 2 Summary of Results

*MPV - Most Probable Value

IV. DISCUSSION

The distribution functions of burning time of aluminum and magnesium have a distinct maximum for 3.75 ms. The longest burning time for aluminum was 26.5 ms and the longest burning time for magnesium was 14 ms.

Prachukho et. al., [5] measured burning time of 1 ms for 90 μm magnesium particles in water vapor, pressure of 1 ATM and at ambient temperature of 1800°C. Considering our different experimental conditions (about 175 μm particles and pressure of 1.5-2 ATM) and the fact that the burning time increases with the pressure and particle size we can conclude agreement with our results (burning time of 3.75 ms). Ozerov et. al., [6] measured burning time of 18 ms in water-vapor for 120 μm aluminum particles and burning time of 12 ms for 165 μm magnesium particles in Prachukho's conditions and apparatus. These results are slightly longer than our burning time results but are longer than Prachukho's results as well.

The distribution functions of burning time for zirconium, tantalum and pyrofuze are more uniformly distributed over longer burning times than that of aluminum and magnesium, especially those of tantalum and pyrofuze where burning times as long as 95 ms were found. Published literature related to tantalum and pyrofuze burning time was not found. Harrison [8] reported the same qualitive results about zirconium burning time. He suggested that in zirconium there is surface burning of the molten metal instead of burning taking place in the vapor phase in magnesium (and aluminum). We believe that we have the same behavior for tantalum and pyrofuze combustion in steam.

Nelson et. al., [7] and Leibovitz et. al., [3] measured burning time of bigger zirconium and aluminum particles, respectively, by laser heating and found much longer burning times in excess of 200 ms. We believe that the different heating technique and different particle size were responsible for such a long burning times.

Comparing the distribution functions of burning time to distribution functions of particle size, though measured in two following sets of experiments because of obvious reasons, one can conclude a statistical proportion between burning time and particle size. We believe that for zirconium, tantalum and pyrofuze particles there are missing data for burning times shorter than 8 ms due to using small apertures during the experiments. The apertures were determined according to the exposure range of the films, from one side, and the relatively intense illumination from big burning particles from the other side.

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